SPECTRUM SENSING METHODS IN COGNITIVE RADIO NETWORK

A Thesis Submitted In Partial Fulfillment of The Requirements For The Degree of

Bachelor of Technology

In

Electronics and Communication Engineering

By

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CERTIFICATE

This is to certify that the work in the thesis entitled, "***SPECTRUM SENSING METHODS IN COGNITIVE RADIO NETWORK***" submitted by ***GAURAV PANDA and DIBYESH KUMAR HOTA*** is a record of an original research work carried out by them during 2013-2014 under my supervision and guidance in partial fulfilment of the requirement for the award of Bachelor of Technology Degree in Electronics & Communication Engineering, National Institute of Technology, Rourkela. Neither this thesis nor any part of it has been submitted for any degree or diploma elsewhere.

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GAURAV PANDA DIBYESH KUMAR HOTA

ABSTRACT

Cognitive radio is a capable technology, which has provided a different way to increase the efficiency of the electromagnetic spectrum utilization. CR allows unlicensed users or secondary users (SUs) to use the licensed spectrum through dynamic channel assignment strategies or spectrum access when the primary users (PUs) are in a dormant state to improve the spectrum utilization and hence avoid spectrum scarcity. For this we need intelligent spectrum sensing techniques which can detect the presence of spectrum holes and allocate them to the secondary users without interfering with the activities of the primary users. This thesis specifically investigates the Cyclo-stationary detector, the energy detector and their simulation in MATLAB to know the presence of licensed users.

Energy detector is a semi blind spectrum sensing technique, which do not need any prior information about the signal to know the presence of primary users. It is simple and easy to implement, but requires high SNR conditions for optimal performance, which is in accordance with our simulation results. The poor performance of ED in low SNR conditions provides option for new spectrum sensing techniques which performs better in LOW SNR conditions. In that Sense the Cyclo-stationary detector overcomes the problem as it gives optimal performance even at low SNR conditions.

The wireless microphone signal which is specified in IEEE 802.22 standard (first standard based on cognitive radio) is used as the test signal for the performance evaluation of the energy detector as well as the cyclo-stationary detector.

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LIST OF FIGURES:-

LIST OF ABBREVIATIONS:-

ADC	Analog to Digital Converter
CAF	Cyclic Auto-correlation Function
CSD	Cyclic Spectrum Density
DVB-T	Digital Video Broadcast - Terrestrial
LNA	Low Noise Amplifier
PDF	Probability Density Function
PSD	Power Spectrum Density
PU	Primary User
ROC	Receiver Operating Characteristics
SNR	Signal to Noise Ratio
SU	Secondary User
Pfa	Probability of False alarm
Pd	Probability of detection
Pmd	Probability of missed detection
SSCA	Strip spectral correlation analysis
CDF	Cyclic Domain Profile
CS	Cyclic Spectrum

Chapter 1: Introduction

1.1. History of cognitive radio

In recent times the requirement for a robust and flexible wireless communication has become more evident. The union of the mobile communication systems and the internet technologies is thought as the future of wireless networks to provide a wide range of service to the customers.

The conventional method of electro-magnetic spectrum licensing and then utilizing it gave rise to static and inefficient use of the available spectrum. The market demand and the need of different technologies has led to the unbalanced use of the spectrum and hence spectrum scarcity. The solution to the above problem required the introduction of innovative licensing policies and proper co-ordination infrastructure which will enable dynamic use of the radio spectrum and hence will increase the spectrum efficiency.

Cognitive radio provides the promising solution to all these challenges. Cognitive radio has a smart layer which performs the learning of the environment to get better results in unknown and dynamic situations. It permits an interactive and easy way of utilizing the electro-magnetic spectrum and the communication resources between market, different technologies and the regulations.

The subsequent steps highlight from the origin of the cognitive radio to its development till the contemporary [1] time:-

- The term cognitive radio was coined for the first time by Joseph Mitola III in his doctoral thesis [2] in 1999.
- In 2002, the Next Generation (DARPA-XG) program was funded by the Defense Advanced Research Projects Agency (DARPA). The main objective of the program was to create a spectrum management framework based on policies so that the radios can use the available spectrum (spectrum holes) present in time and space.

- This action led to the attention of the FCC (Federal Communications Commission), which by then, based on a research piloted by it, had confirmed the underutilisation of the spectrum bands. Sometimes later the FCC issued the Notice for Proposed Rule Making (NPRM) [3], which aimed at exploring the CR technology to enable efficient spectrum management.
- The Institute of Electrical and Electronic Engineers (IEEE), in 2004, designed the 802.22 working group to define the Wireless Regional Area Network (WRAN) , Physical (PHY) and Medium Access Control (MAC) layer specifications.
- The Institute of Electrical and Electronic Engineers (IEEE), by the end of 2005, IEEE started the Project 1900 standard task group for the next generation radio and electro-magnetic spectrum management. This project aimed at giving standard terms and the definitions for interference and co-existence analysis, spectrum management, dynamic spectrum access radio systems.
- IEEE organized its first conference based on cognitive radio CROWNCOM, in 2006, to gather the new ideas about cognitive radio from a varied set of researchers from all around the world.
- This conference was followed by the launch of the FCC’s TV band unlicensed service project which used cognitive radio technology.
- By the end of 2008, different rules to allow the cognitive devices to work in TV white spaces in secondary basis were launched by the Federal Communications Commission (FCC).
- FCC defined a Memorandum Opinion and Order which determined the ultimate rules to use the white space by secondary wireless users(unlicensed users[4]) ,in 2010.
- The IEEE issued IEEE 802.22 (WRAN) as an official standard [5], in July 2011.
- Presently, IEEE is focused on the standards for commended practice for installation and positioning of 802.22 systems.

1.2. Motivation

The cognitive radio offers a very rewarding area of research field. Need of more spectrum due to the underutilisation of the available spectrum is the main motivation behind cognitive radio and implementing it leads to lessening of spectrum scarcity and hence the optimal use of spectrum resources. Spectrum sensing which basically checks for the vacant or unused spectrum band forms the main part of the cognitive radio. There are different schemes based on which spectrum sensing is done like energy detector, matched filter detector, Cyclo-stationary detector, Eigen value based sensing, etc. Energy detector works very well in high SNR environments, matched filter detector needs much more information about the signal which is called priori information and the complexity of other two is high. These constraints led to search for an optimal detector which performs well under low SNR conditions as well and with a complexity not so high. This thesis discusses all these performance metrics in details with exclusive mathematical proof.

1.3. Thesis Layout

Chapter 1 – Introduction

In this chapter the history of cognitive radio is discussed, right from the beginning when the term was named to the present day. The reason or motivation behind choosing spectrum sensing in cognitive radio for research is discussed.

Chapter 2 – Cognitive Radio

The second chapter focusses on the basic terminologies related to cognitive radio, its physical architecture. Different spectrum sensing algorithms are discussed in detail with their block diagram and flow charts. Their advantages and disadvantages are discussed vividly with more focus on the energy detector and Cyclo-stationary detector.

Chapter 3-cyclic Spectrum Analysis

The advantages of cyclic spectral analysis over conventional spectral analysis is discussed when communication signals are taken as cyclic stationary instead of statistically stationary. SSCA,(Strip spectral correlation algorithm), the best available algorithm to determine the digital cyclic spectrum, is discussed in detail and shown how it is implemented in cyclo-stationary detector.

Chapter 4- Simulations and Results

The energy detector and Cyclo-stationary detector are implemented in MATLAB and their simulation results are presented in this chapter. The results are thoroughly investigated and analysed. Their merits and shortcomings are compared with each other.

Chapter 5- Conclusion and future work

The overall conclusion of the thesis and some of the future research areas which can be taken up in this field are outlined in this section.

Based on the results obtained in the simulations the merits and demerits of the two implemented spectrum sensing method we have proposed a combined method which will use the spectrum efficiently without unnecessary complexity.

Chapter 2: Cognitive Radio- Literature Review

2.1. Cognitive radio

2.1.1 Features

The formal definition of the Cognitive Radio is given as in [3]:-

"*Cognitive Radio is a radio for wireless communications in which either a network or a wireless node changes its transmission or reception parameters based on the interaction with the environment to communicate effectively without interfering with the licensed users*."

If we observe the frequency range between 80 MHz to 750MHz, then this frequency range can be sub-divided into three different sub-categories which are given as the following:-

- Spectrum bands which remain empty most of the stretch
- Spectrum bands which are partially occupied
- Spectrum bands which re Congested Bands

Our attention for the cognitive radio users lies in the spectrum band which is left unused or remains empty most of the time. In common terms, the cognitive radio provides a new method to use the unused or empty licensed spectrum by temporarily allocating it to the secondary users in such a way that they do not interfere with the primary users or the interference to the paid users is kept to a minimum.

For the secondary or unlicensed users being able to use the licensed spectrum the following precautionary measures should be taken, like [29]:-

- The frequency band should be scanned thoroughly to determine different empty bands
- The best available spectrum band should be selected for the secondary user. The selection can be made on the basis of requirement of the secondary user's application.
- The power level must be kept to the minimum possible value before transmitting on the selected bands to avoid interference with other users. It will also help in, maximizing the number of unlicensed/secondary users of the spectrum of interest.

- The modulation scheme which is used can be varied depending upon the error performance requirement or the distance. Using the lower order modulation technique, for example QPSK lower data rates can be obtained. On the other hand, higher data rate can be achieved by implementing 64-QAM.
- To allow the secondary users to access the empty bands spectrum sharing must be allowed. The frequency bands must be thoroughly checked for any of the Pus entering to transmit in the same frequency range, even after the start of the transmission.

Continuous awareness, Power control, Dynamic frequency selection, Adaptive modulation, frequency agility and frequency negotiation are one those unique features of the cognitive radio which are described above. These steps are better shown in the below mentioned figure 2.1 which is known as the cognitive cycle.

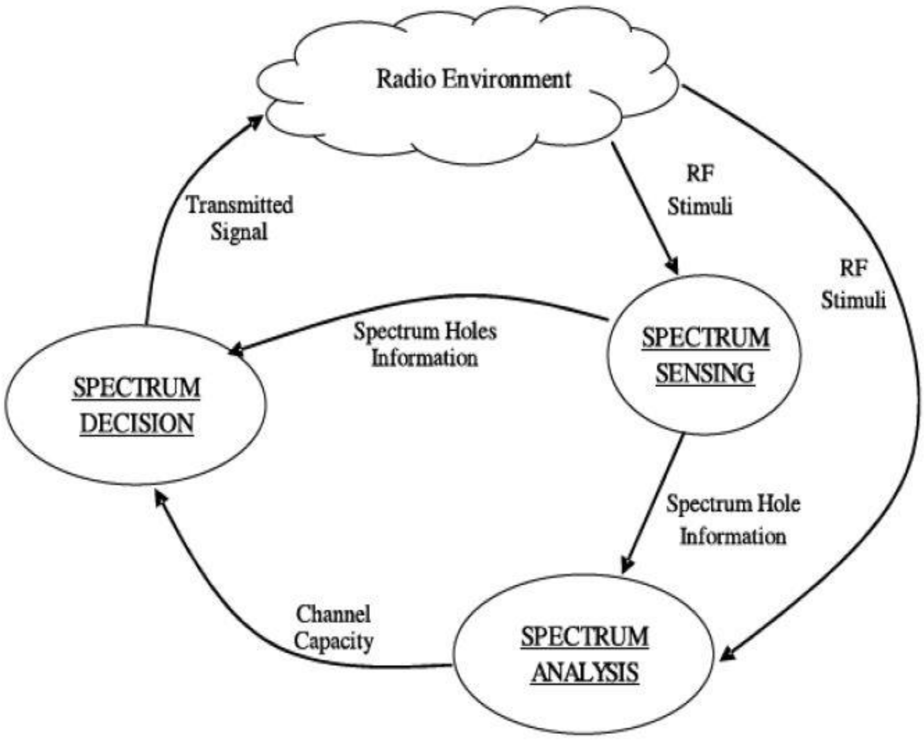


Figure 2.1: Cognitive cycle [30]

Thus, from the information cycle, we came to know the two most important characteristics of the cognitive radio and they are:-

- **Cognitive capability**:-

Cognitive capability refers to the capability of the CR to know its surrounding environment or the channels which are used for transmission and then develop the information about the state in which the channels are. It incorporates the basic functions of the cognitive radio like sensing the spectrum, analyzing it and making the appropriate decisions. And hence finding the appropriate spectrum hole, then selecting the best of all available options and then finalizing the parameters for transmission which comes under this category.

- **Reconfigurability**:-

Reconfigurability refers to programming the radio dynamically keeping the hardware section unchanged. Cognitive radio basically is a software based not hardware based radio. So it can support a number of applications and shift between different wireless protocols. The reconfigurability property of the cognitive radio is given by the software based approach. This makes it possible to shift between different frequencies, monitor the power levels without changing hardware [7] [8] and change the modulation scheme.

2.1.2 Physical Architecture

The CR uses a transceiver which consists of the RF front end and a baseband signal processing unit. The baseband unit performs modulation/demodulation and encoding or decoding functions [7]. The RF front end given by figure 2-2 consists of:-

- **RF Filter**:-

This filter is a band-pass filter which is used to discard the unwanted spectrum and hence select the frequency of interest.

- **Low noise amplifier (LNA):-**

It is generally used for amplifying the incoming signal. It plays a major role in determining the overall noise figure of the system as is given by Frii’s formula.

- **Mixer:-**

Frequency translation is achieved by using the mixer. The RF frequency is converted to the IF frequency as processing the signals in lower frequency is easy and designing the appropriate filters are possible at lower frequency.

- **Phase locked loop (PLL) and Voltage Controlled Oscillator (VCO):-**

The voltage controlled oscillator (VCO) is used to generate a signal with fixed frequency which is used for mixing. The PLL makes sure that the frequency remains constant with time by the feedback loop.

- **Channel Selection Filter:-**

It is used for rejecting the adjacent bands by selecting the desired frequency bands.

- **Automatic Gain Control (AGC):-**

It is used to keep the output power level almost constant over a wide range of the input signals.

- **A/D converter:-**

It samples, then quantizes and then encodes the Analog signal to convert it to the digital signal which can be processed by the baseband processing unit.

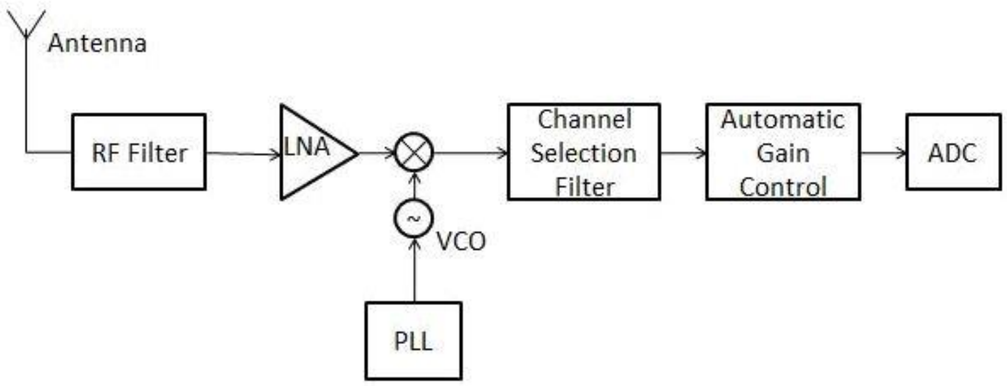


Figure 2.2: RF Front end of a receiver

2.1. Spectrum sensing

Spectrum sensing is defined as the capability of the CR to allocate the best available unused or ideal licensed spectrum to the secondary users (SUs) satisfying their Quality of service (QoS) but without causing any interference to the primary or licensed users.

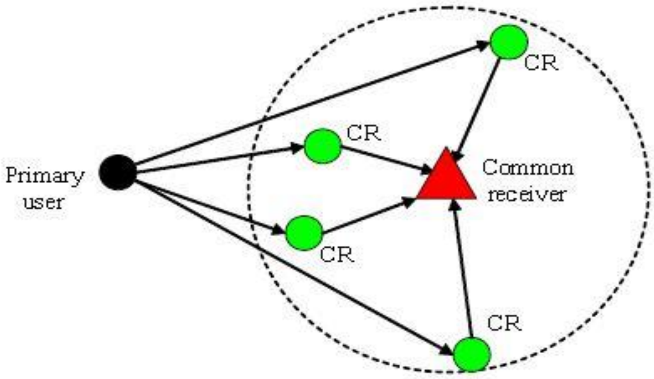


Figure 2.3: Spectrum sensing structure in a cognitive radio network [14]

2.2.1 Analytical Model (Two hypothesis)

One of the most important elements in the cognitive radio network is spectrum sensing. For communication to take place in fact, it is the first step that needs to be performed. Spectrum sensing can be thought of an identification problem, popularly known as the hypothesis test [11]. The sensing algorithm has to just decide one of the following two hypotheses:-

$$H1: x(t) = s(t) + n(t)$$

$$H0: x(t) = n(t)$$

S (t) is the signal that is transmitted by the PUs.

X (t) is the signal which is received by the SUs.

N (t) is known as the AWGN (Additive White Gaussian noise).

- H0 hypothesis tells that no primary signals are present in the spectrum and only noise is present. And hence it can be allotted to the secondary users.
- H1 hypothesis tells that primary signals are present in the spectrum along with the noise. And hence it cannot be allotted to the secondary users else it will cause harmful interference to the primary users.

Probability of false alarm:-

Probability of false alarm, as the name indicates happens when no primary signals are present in the spectrum but we get the idea that they are present and hence do not allocate it to other SUs. It happens when only noise is present in the channel and energy of noise present exceed the predefined threshold value and hence the decision making device detects the presence of primary users. This is unwanted and hence should be minimized.

Probability of missed detection:-

Probability of missed detection, as the name indicates happens when primary signals are present in the spectrum but we get the idea that they are not present and hence allocate it to other SUs. This causes interference to the primary users. It happens when a signal is present in the channel and energy of signal present do not exceed the predefined threshold value and hence the decision making device doesn't detect the presence of primary users. This is unwanted and hence should be minimized. The below diagram shows the trade-off between Pmd and Pfa with respect to the threshold value:

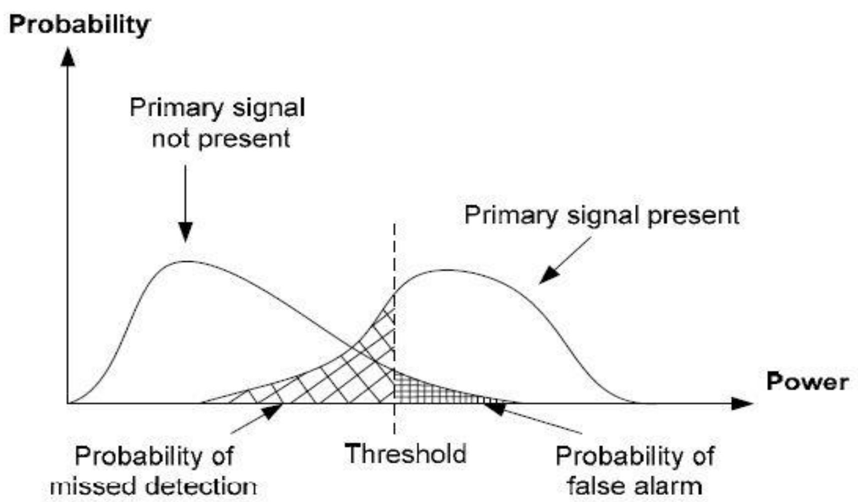


Figure 2.4: PDFs for hypothesis testing problem [31]

- As we can see decreasing the threshold value to decrease the probability of missed detection would increase the probability of false alarm and increasing the threshold value to decrease the probability of false alarm would increase the probability of missed detection. Since both are unwanted and both can’t be decreased simultaneously, hence trade-off between these two parameters is done and the threshold is set accordingly.

2.2.2 Energy detector

Energy detection is a non-coherent method of spectrum sensing which is used in detecting the presence of primary signal in the frequency spectrum being sensed. This type of sensing technique is popular because it does not require prior knowledge of primary signal and it is simple. In both time and frequency domain energy of the signal is preserved. Figure 2.4 shows the time domain representation of the energy detection method and Figure 2.5 shows the frequency domain implementation. But whichever representation we use, there is no difference in the eventual result. However, pre-filter matched to the bandwidth of the signal is required in the time domain representation. It makes time domain representation relatively inflexible compared to the other. So it is desirable to use the frequency representation for analyzing the received signal. The physical implementation of the detection method is shown below both for time and frequency domain:-

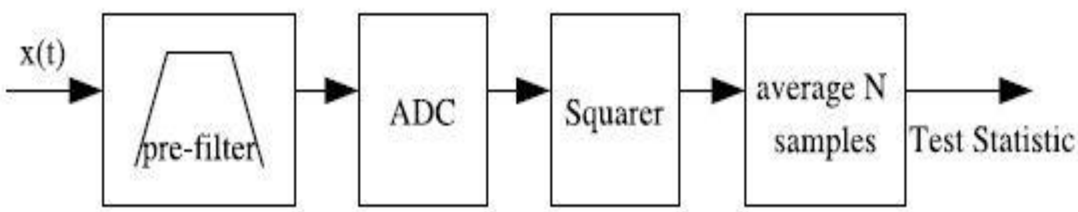


Figure 2.5: Representation of energy detection mechanism in time domain [17]

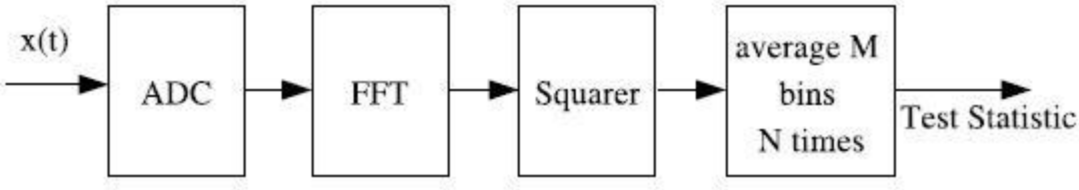


Figure 2.6: Frequency domain representation of energy detection mechanism [17]

The flow chart of the energy detection is depicted in Figure 2.6. In this technique signal is made to pass through the BPF with a band bandwidth W followed by integration over the time interval. The threshold calculated by the below mentioned formula is compared with the output received from the Integrator. Whether the primary or licensed user is present or not is discovered from the comparison.

Energy detection is also known as Blind signal detector as the characteristics of the signal is ignored by it. The presence of a signal is estimated by the comparison of receiving energy with a threshold v calculated from noise statistics.

The threshold for energy detection is calculated from the formula given below [10]:-

$$Q_0 = \frac{1}{\sqrt{8\pi \mathrm{TW}}} \int_{V'_T}^{\infty} exp\left[-\frac{(x-2TW)^2}{8TW}\right] dx$$

$$= \frac{1}{2} erfc\left[\frac{V'_T - 2TW}{2\sqrt{2}\,\sqrt{TW}}\right]$$

Where

V_T =Threshold Voltage

Q_0=Probability of false alarm=Pfa

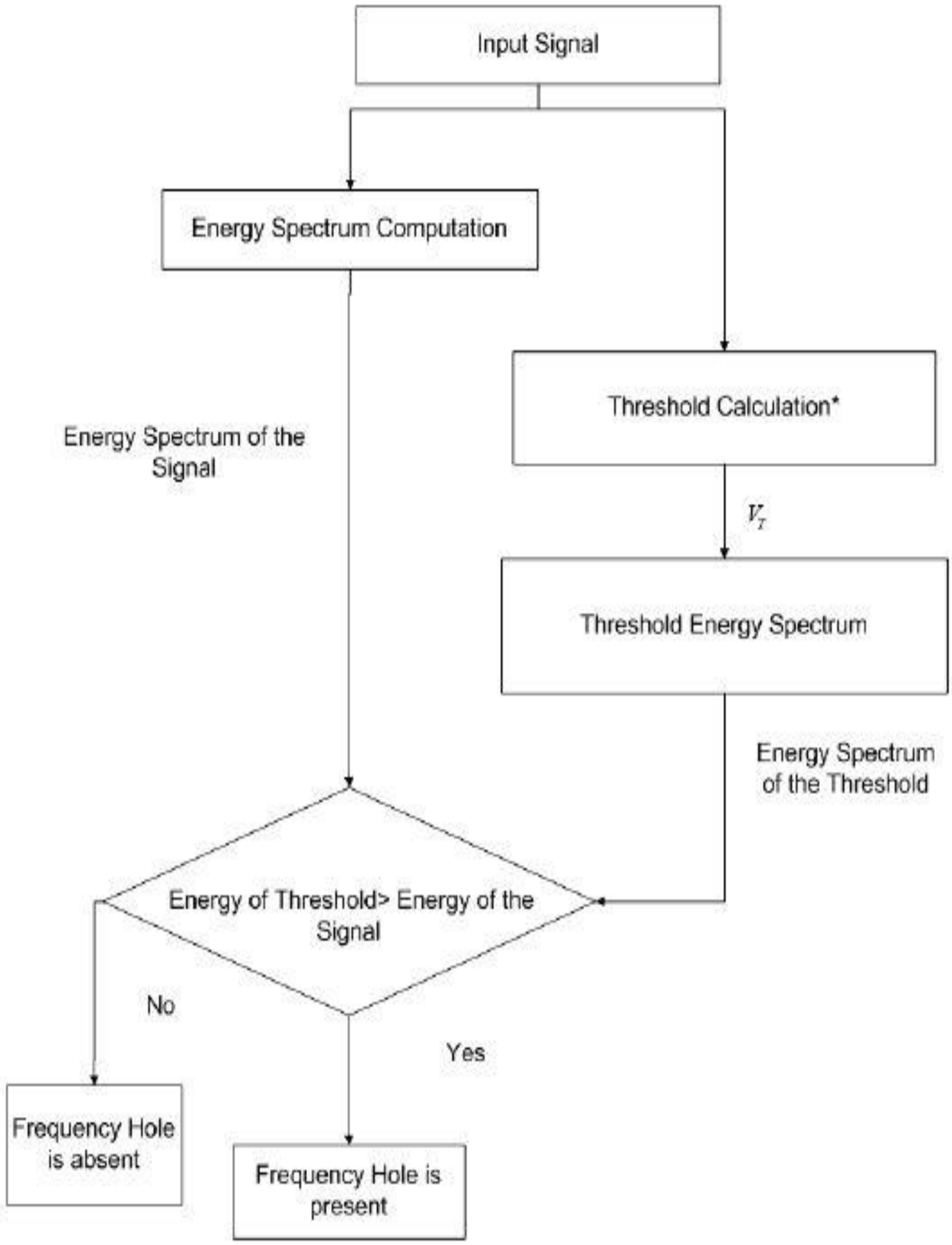


Figure 2.7: Conventional energy detection method [22]

The practical implementation of Energy detection spectrum sensing is done in MATLAB with the given below architecture:-

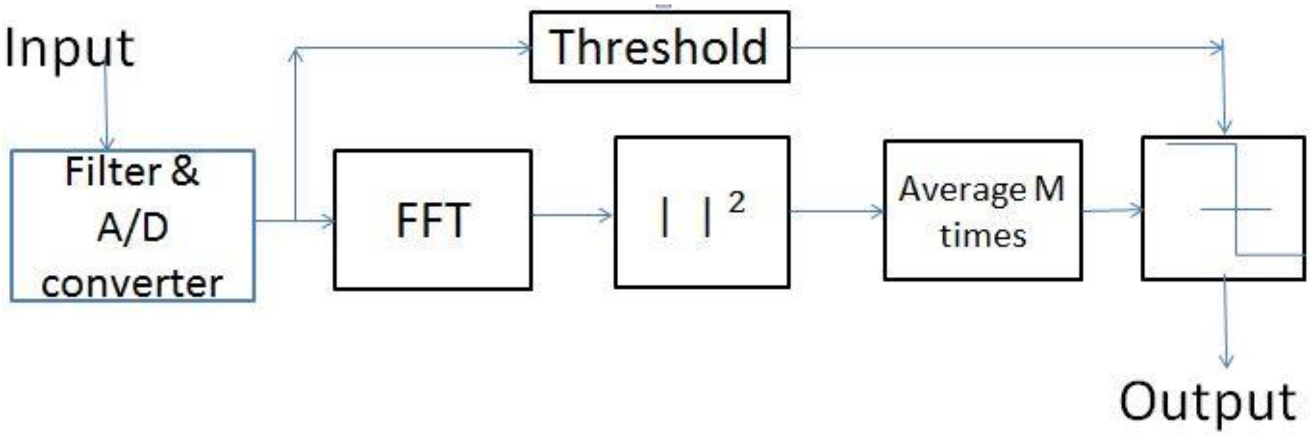


Figure 2.8: Implementation of Energy detection using Welch's periodogram [31]

A threshold value is needed for comparison of the energy found by the detector. More energy than the threshold values indicates the presence of the primary user.

Advantages:-

- It is easy to implement
- Computational complexity is low
- No priori information is required

Disadvantages:-

- Does not perform well in low SNR conditions
- Cannot properly distinguish between primary signal and noise

2.2.3 Matched Filter Detection

Matched filter is designed to maximize the output SNR for a given input signal. MF detection is applied when the secondary used has prior knowledge of the residing user. In matched filter operation convolution of the unknown signal is done with the filter whose impulse response is time shifted & mirrored with respect to the desired signal. The expression for Matched filter is expressed as:

$$Y[m]=\sum_{k=-\infty}^{\infty} x[k]h[m-k]$$

Where the unknown signal is ‘x’ and the impulse response (h) of matched filter that is matched to the reference signal is convolved with it for maximizing the SNR. Matched filter detection is applicable only in cases where the cognitive users know the data from the primary user.

The block diagram of implementation of matched filter spectrum sensing algorithm is given below:-

Figure 2.9: block diagram of matched filter detection

Advantages:-

- Since it maximizes the SNR, it is the desirable detector
- The sensing time is low as compared to other detectors

Disadvantages:-

- Prior knowledge of the primary user signal is required

2.2.4 Cyclo-stationary Feature Detector

In telecommunication, sonar and radar fields periodicity arises because of modulation, coding etc. There might be a case where all the parameters are not periodic with respect to time, but their statistical features are periodic and these processes are called Cyclo-stationary processes.

A wide sense stationary process that exhibits Cyclo-stationarity has both mean and auto-correlation function periodic in time domain. When the Fourier series expansion is done of the auto-correlation function, it is found that the function only depends on the lag parameter which happens to be frequency. There is absolutely no correlation between spectral components of a wide sense Cyclo-stationary process. Cyclic Auto-correlation Function (CAF) is the Fourier series expansion and the lag parameter is known as cyclic frequency.

The reciprocal of the period of Cyclo-stationarity multiplied by n (any integer) gives cyclic frequency. Now when the Fourier transform of Cyclic autocorrelation function is taken, Cyclic spectral Density(CSD) is obtained and it shows the density of the correlation between two spectral components ,are separated by one cyclic frequency.

The essential conditions to be obeyed by a process to be wide sense Cyclo-stationary

$$E[x(t+T_0)] = E[x(t)]$$

$$R_X(t+T_0,\ \tau) = R_X(t,\ \tau)$$

$$Here\ R_X = E\{\ x(t+\tau)\ x(t)\}$$

Thus, both the mean and auto-correlation function for such a process needs to be periodic with some period say T_0.

Since the auto correlation is periodic it can be expressed as Fourier series as given below [11]

$$R_x\left(t+\frac{\tau}{2}, t-\frac{\tau}{2}\right) = \sum_{\alpha} R_x^{\alpha}(\tau) e^{j2\pi\alpha t}$$

Also the auto correlation function can be expressed in the following manner

$$R_x\left(t+\frac{\tau}{2}, t-\frac{\tau}{2}\right) = \left\langle x\left(t+\frac{\tau}{2}\right) x^*\left(t-\frac{\tau}{2}\right)\right\rangle$$

Where, x* (.) denotes the complex conjugate of x (.) and <. > is the time-averaging operation

$$\langle\ .\ \rangle \triangleq \lim_{T\to\infty} \frac{1}{T}\int_{-T/2}^{T/2} (\ .\ )\, dt$$

Where, Rx (t) =CAF (Cyclic Auto correlation Function) is given by

$$R_x^{\alpha}(\tau) = \left\langle R_x\left(t+\frac{\tau}{2}, t-\frac{\tau}{2}\right) e^{-j2\pi\alpha t}\right\rangle$$

The cyclic spectral density (CSD) representing the time averaged correlation between two spectral components of a process which are separated in frequencies by *'α'* is given as

$$S_x^{\alpha}(f) = \mathcal{F}(R_x^{\alpha}(\tau)) = \int_{-\infty}^{\infty} R_x^{\alpha}(\tau)e^{-j2\pi f\tau}d\tau$$

When ‘α=0’ for CSD, the special case is known as Power spectral density (PSD). It can also be obtained by taking the Fourier transform of the cyclic auto correlation for α=0.

The periodicities of primary user signal can be found out simply by taking their correlation which enhances their similarities. When the Fourier transform of the correlated signals are taken peaks at frequencies are obtained which are specific to a signal and primary user’s presence can be determined be searching for these peaks. As Noise is a random signal, no peak is obtained due to its correlation and hence it does not get highlighted. Only peak due to noise is obtained at α=0.

The implementation of the Cyclo-stationary detector is given below, which shows the steps to implement it. The CSD is obtained by the SSCA algorithm described in the chapter 3. The peaks are observed in the CSD and maximum of the peaks is compared with the threshold. If the maximum of the peaks is greater than the threshold, then primary user is present else it is absent.

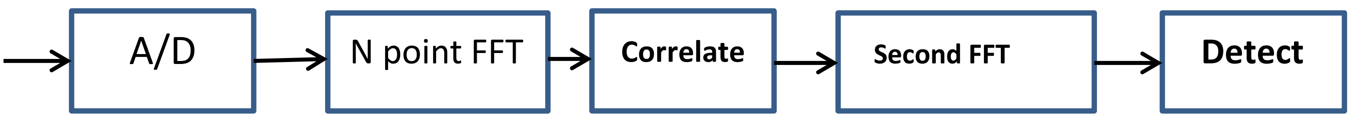


Figure 2.10: Implementation of cyclo-stationary detector

Algorithm to implement Cyclo-stationary detector:-

1. Implement the SSCA algorithm as described in chapter 3
2. SSCA will give the three dimensional Cyclic Spectral Density plot
3. Determine the maximum of the peaks observed in the CSD plot
4. Compare it with the threshold
5. If the maximum of the peaks is greater than the threshold, then primary user is present else it is absent.

Chapter 3: Cyclic Spectral Analysis

3.1. Need of cyclic spectrum

Most signal processing methods deal with signals assumed to be statistically stationary. However, in communication systems, most man-made signals do not meet the stationary assumption and are in fact better modelled as Cyclo-stationary processes where the statistical parameters of the signals are assumed to be varied with time [11]. This motivates the need to perform cyclic spectral analysis, allowing identification of underlying periodicities.

In this report, it is shown how the cyclic spectral analysis is much superior to the conventional spectral analysis which we generally perform. The three main benefits of using cyclic spectral analysis are:-

- Even in highly noisy or corrupted environment signals can be selectively selected because if the signals have even a slightly different characteristics they can be discriminated in the cyclic spectrum
- Since cyclic spectrum is computed over a large no of data, so it provides a greater domain for signal analysis and hence gives more information about desired signal.
- The correlation between the spectrums of the signals provides a complete process for modelling the communication signals which are used in several applications.

Most signal processing methods when dealing with communications signals typically assume them as being statistically stationary, i.e., signals whose statistical parameters, such as mean and variance, do not vary with time. Then the signal is modelled as a one-dimensional autocorrelation function. Then the Fourier transform of the auto correlation function is taken to give the power spectral density (PSD). However, it is known that most man-made signals encountered in radio communication systems are in fact Cyclo-stationary [12], that is, statistical parameters are periodically or cyclically stationary. Modelling the signal as Cyclo-stationary results in a two-dimensional autocorrelation function where the extra dimension is denoted α, i.e., the cycle frequency at which the one-dimensional autocorrelation function has been computed. For each a, a F.T. of the cyclic autocorrelation function produces a cyclic-spectrum-cut for that particular frequency separation α.

CS analysis is more powerful in detecting the signal features because even for the signals which have their features overlapping in power spectrum will have non-overlapping characteristics in cyclic spectrum.

3.2. Implementation of SSCA algorithm

Strip Spectral Correlation Algorithm (SSCA) is one of the best digital CS estimation algorithms derived so far. It is preferred over FAM algorithm to determine the cyclic spectrum because of its lower computational complexity.

The Strip Spectral Correlation Algorithm implements the Fourier transform of the correlation products between the spectral component and its conjugate components, both of which are smoothed over time [6]. Then the periodicities in the spectral components, then become detectable. The cyclic spectral plane consists of the spectral frequency, the cyclic frequency and the FFT of the correlation function. The spectral frequency ranges from -fs/2 to +fs/2 and the cycle frequency ranges from **-fs** to **+fs** where **fs** is the sampling frequency.

The SSCA is implemented by forming a two dimensional array from x (kT), where k lies between 0 to N-1. The array contains rows of length N’ of the input sample data. L is a parameter defined known as the offset. Each succeeding row starts with an offset of L samples from the previous row starting position. Then each row of the array passes through the hamming window to reduce the spectral leakage and Fourier transform is applied to each row to know the spectral components. After this the signals are down converted to baseband frequencies by frequency shifting operation. Then transpose of each row is taken and is replicated L times to form an array of dimension N’xPL. Then it is multiplied with the conjugate of the input signal column wise to give the cyclic auto-correlation function. Fourier transform of this array is done row wise and are placed on a strip of the final cyclic spectral plane to give the require cyclic spectral density. A block diagram for the SSCA cross-spectral estimate is given by Figure 2.7.

The following subsections discuss in detail how the SSCA is implemented to determine the cyclic spectrum of the signal step by step. We are given with the following parameters:-

N=No of input samples
N'=No of input channels
L=Offset
P= (N-N') /L
Δf = *fs/N'*=frequency resolution
$\Delta\alpha$=cycle frequency resolution
Fs=sampling rate of the signal
$\Delta t \Delta f$ = *N/N'*

While taking the inputs the following things should be taken care of:-

- N' should be chosen as a power of 2 to avoid truncation or padding of zeroes.

- L<=N'/4

- $\Delta t \Delta f > 1$

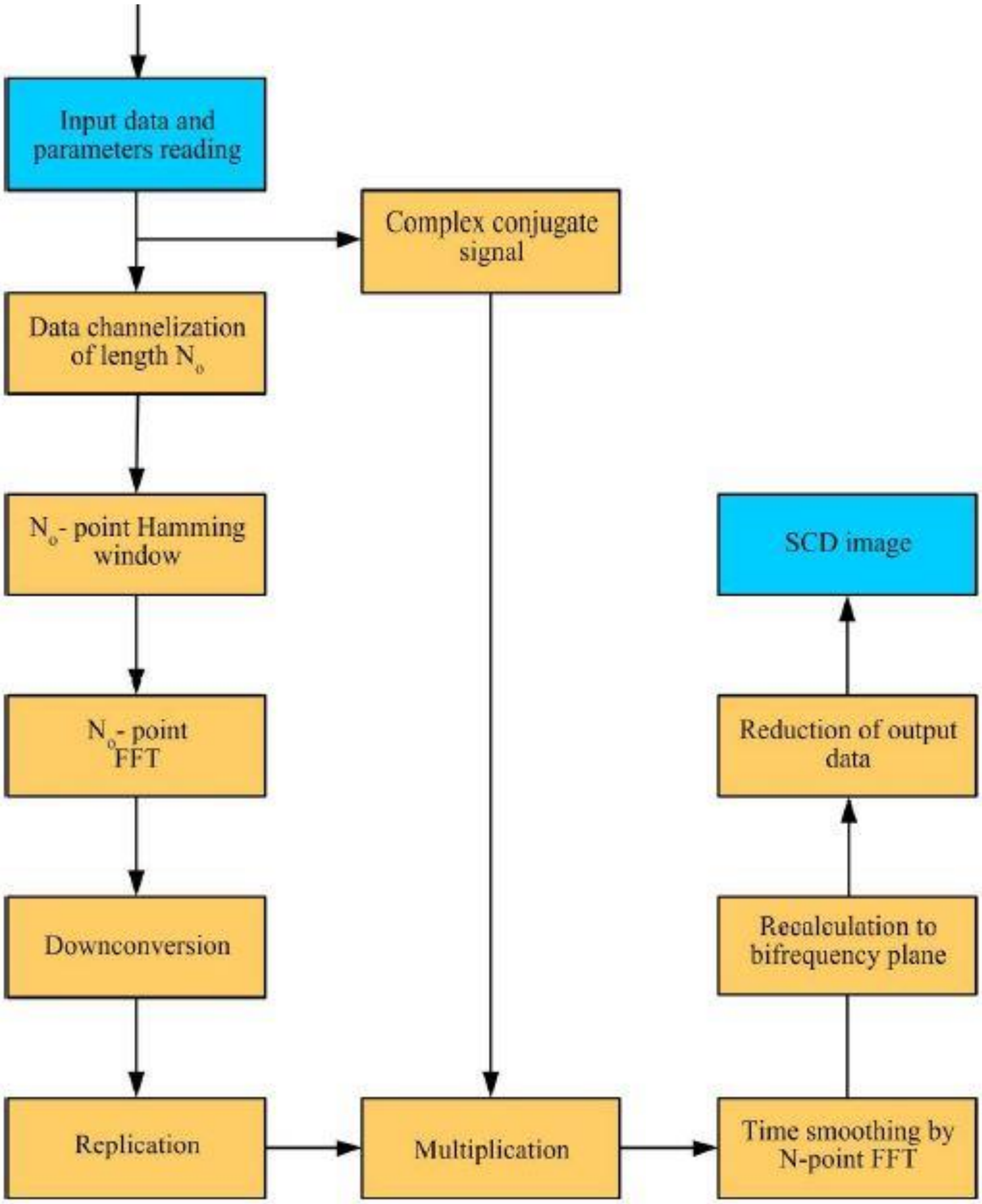


Figure 3.1: block diagram for the SSCA cross-spectral estimate

Algorithm to implement SSCA:-

The algorithm is clearly defined in [6]. The algorithm consists of the following steps as explained below:-

1. **Input Channelization**

It basically refers to the formation of the matrix. From the input samples a two dimensional array is formed with row length=number of columns= N'=number of channels and P rows.

2. **Windowing**

To each row of the array, hamming window is a applied to reduce the spectral leakage and the side lobes. Windows can be of any type, but research shows that Kaiser or hamming window gives the best results.

The Hamming window is given by the following equation:

$$W(r) = \begin{cases} 0.54\text{-}0.46\cos\left(2*n*pi/q\right) & \text{when n is greater than 0 and less than q} \\ 0 & \text{otherwise} \end{cases}$$

3. **First FFT**

Each row of the windowed data array is Fast Fourier transformed to reveal the first spectral components. The resultant array is still indexed P rows by N' columns, but now the column index relates to a specific bin of spectral frequencies.

4. **Down conversion**

Each row of spectral components is down converted to baseband by frequency shifting operations through multiplication with the complex exponential exp (-j*2*pi*m*k*L/N')

where m is the row index, $0 < m < P-1$

k is the column index, $0 < k < \boldsymbol{N'}-1$

5. **Replication**

Each row is copied into one column of an empty $\boldsymbol{N'}$ by PL array. It is then replicated in the L-1 adjacent columns.

6. Multiplication

Each column of the array is point wise multiplied with the conjugate of a sample value y (kT). There are PL-N columns and PL samples from y (kT).

7. **Second FFT**

Each row from the previous multiplication is Fast Fourier transformed to yield a PL-point result. Each resulting vector is stored in a strip of the cyclic spectral plane.

8. Data Reduction

The SSCA Program typically generates large output data files. For convenience, an option may be chosen to reduce the amount of output. By comparison sorting for the largest a value in an (f, α) cell, the number of **a** slices is reduced from N to N/L. Overall SSCA execution time increases accordingly to accomplish the searches.

9. Recalculation to bi frequency plane

It refers to the mapping process in which we normalize the spectral frequency and the cyclic frequency with respect to the sampling frequency.

After all these processes are implemented the cyclic spectrum or the CSD (Cyclic Spectral Density) is obtained.

3.3. Use in Cyclo-stationary spectrum sensing

The three dimensional CSD (cyclic spectral density) is obtained by the SSCA algorithm described above. The peaks are observed in the CSD and maximum of the peaks is compared with the predefined threshold, which depends on the probability of false alarm. If the maximum of the peaks exceeds the threshold, it implies primary user is present else it is absent.

Chapter 4: Simulations and Results

For the testing of the detection algorithms and to determine their performance, we have used the frequency modulated wireless microphone signal which is given by

$$w(t) = \cos\left(2\pi\int_0^t (f_c + f_\Delta w_m(\tau))d\tau\right)$$ where

f_c is the carrier frequency

f_Δ is known as frequency deviation

$w_m(\tau)$ is the original source signal.

The wireless microphone signal is one of the standard signals defined by the IEEE 802.22 Cognitive Radio standard.

Following are the results of the simulations we have obtained by implementing them in MATLAB.

- **Results for energy detector**

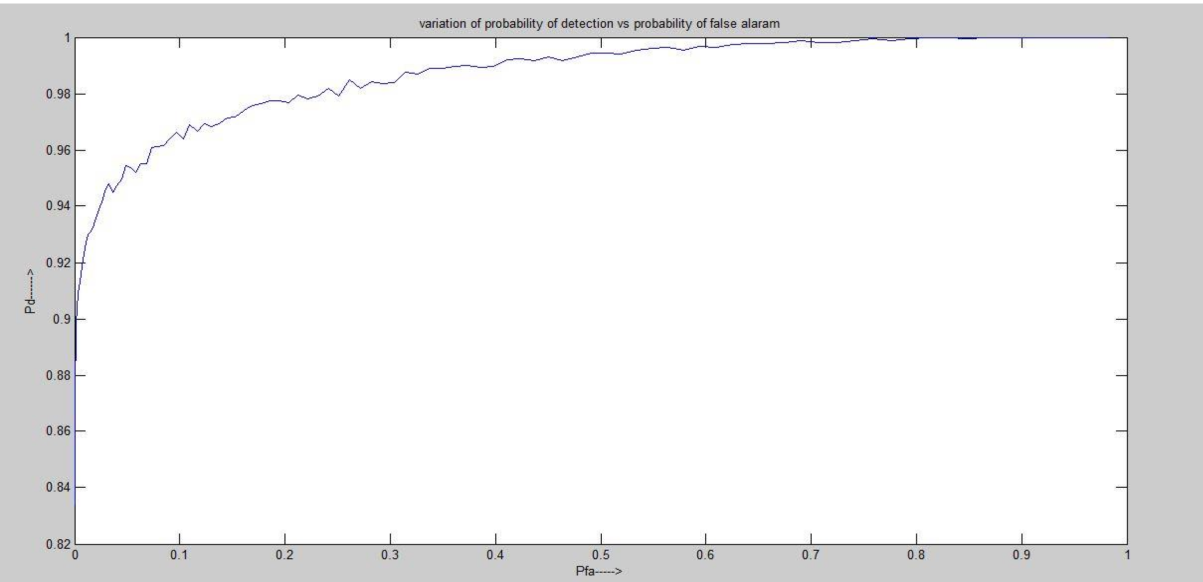


Figure 4.1: **Variation of Pd vs Pfa**

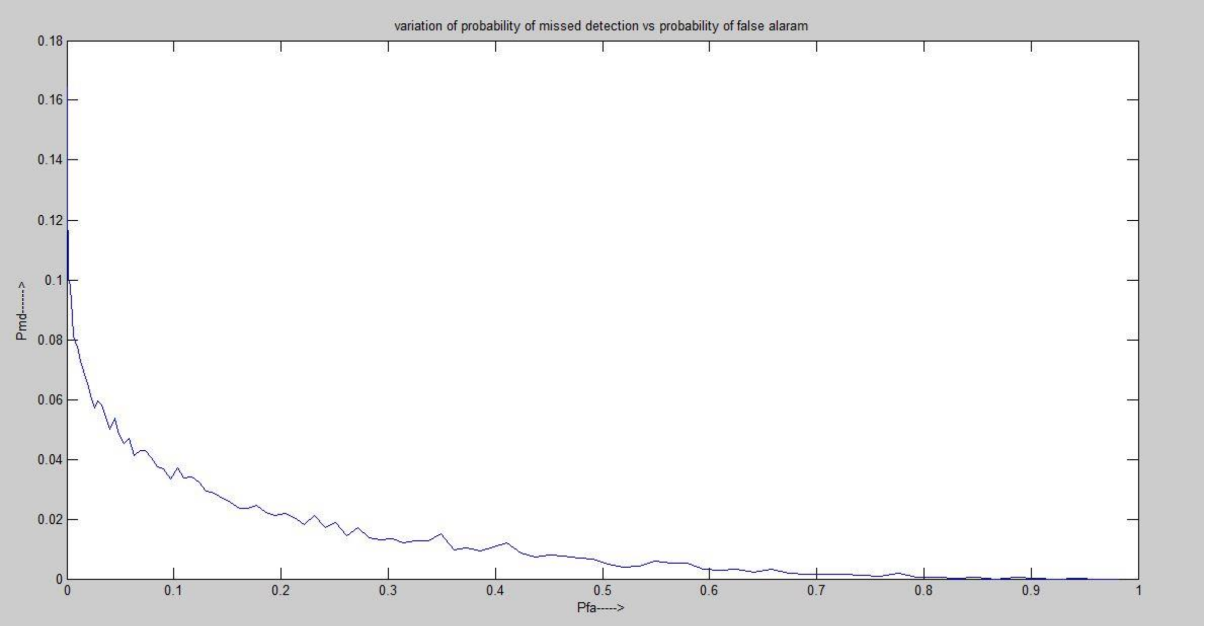


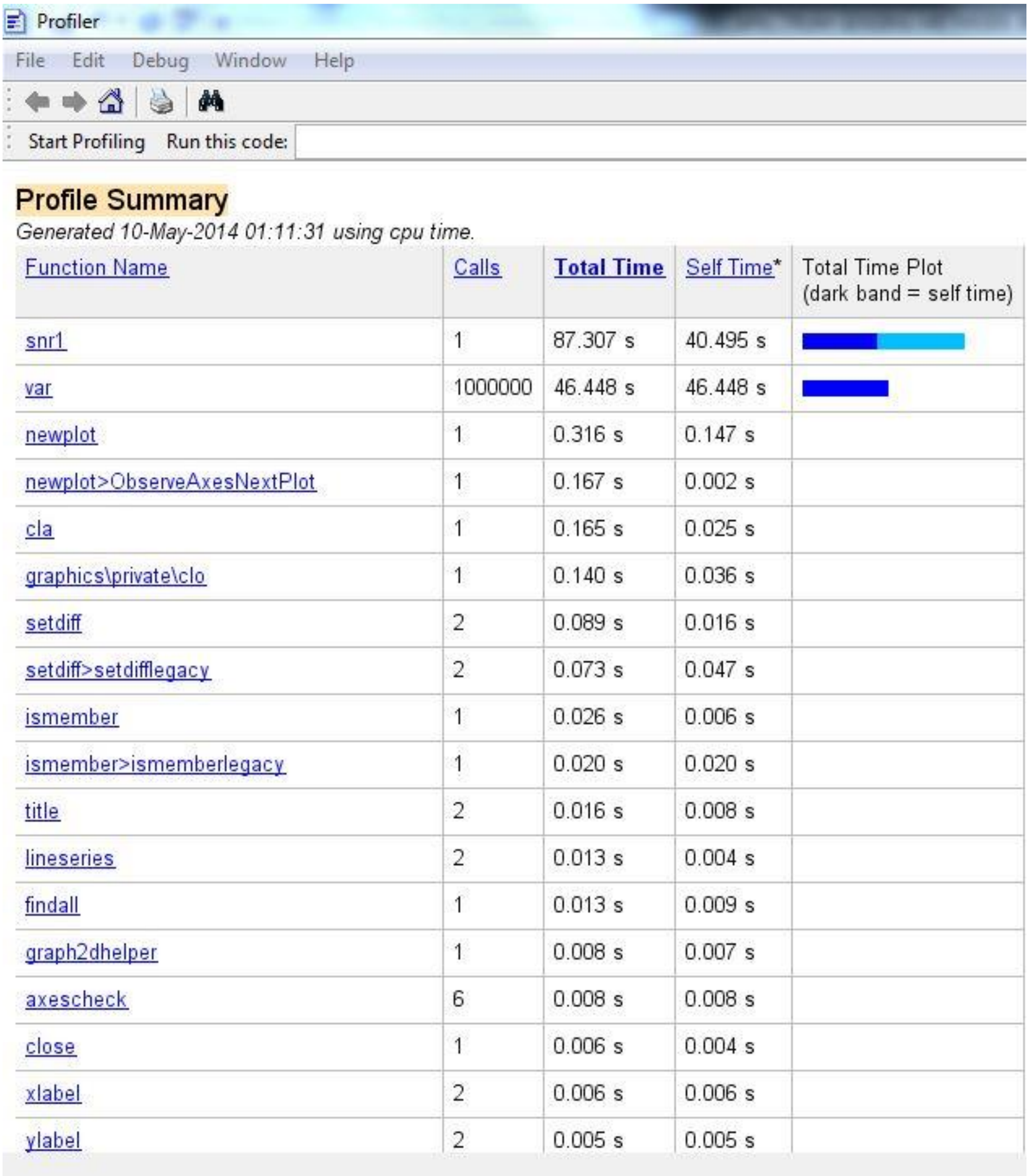
Figure 4.2: **Variation of Pmd vs Pfa**

Pd=Probability of detection

Pmd= Probability of missed detection=1-Pd

Pfa= Probability of false alarm

- The above mention curves are known as the ROC (Receiver operating characteristics) curve.
- As can be seen from the graph of Pmd vs Pfa when Pmd is low, Pfa is high and vice versa.
- As discussed earlier, it is not possible to decrease them both simultaneously. So a trade-off between the two must be done according to the requirements.



Profiler

File Edit Debug Window Help

Start Profiling Run this code:

Profile Summary

Generated 10-May-2014 01:11:31 using cpu time.

Function Name	Calls	Total Time	Self Time*	Total Time Plot (dark band = self time)
snr1	1	87.307 s	40.495 s	
var	1000000	46.448 s	46.448 s	
newplot	1	0.316 s	0.147 s	
newplot>ObserveAxesNextPlot	1	0.167 s	0.002 s	
cla	1	0.165 s	0.025 s	
graphics\private\clo	1	0.140 s	0.036 s	
setdiff	2	0.089 s	0.016 s	
setdiff>setdifflegacy	2	0.073 s	0.047 s	
ismember	1	0.026 s	0.006 s	
ismember>ismemberlegacy	1	0.020 s	0.020 s	
title	2	0.016 s	0.008 s	
lineseries	2	0.013 s	0.004 s	
findall	1	0.013 s	0.009 s	
graph2dhelper	1	0.008 s	0.007 s	
axescheck	6	0.008 s	0.008 s	
close	1	0.006 s	0.004 s	
xlabel	2	0.006 s	0.006 s	
ylabel	2	0.005 s	0.005 s	

Figure 4.3: **profile summary of ROC curve**

- As seen from the profile summary, it takes about 1.5 minutes for the simulation
- Low simulation time is a result of low computational complexity

- The following curves show how the energy detector performs in noisy channel/environments. As seen from graph they perform well only at high SNR values starting from 10dB.

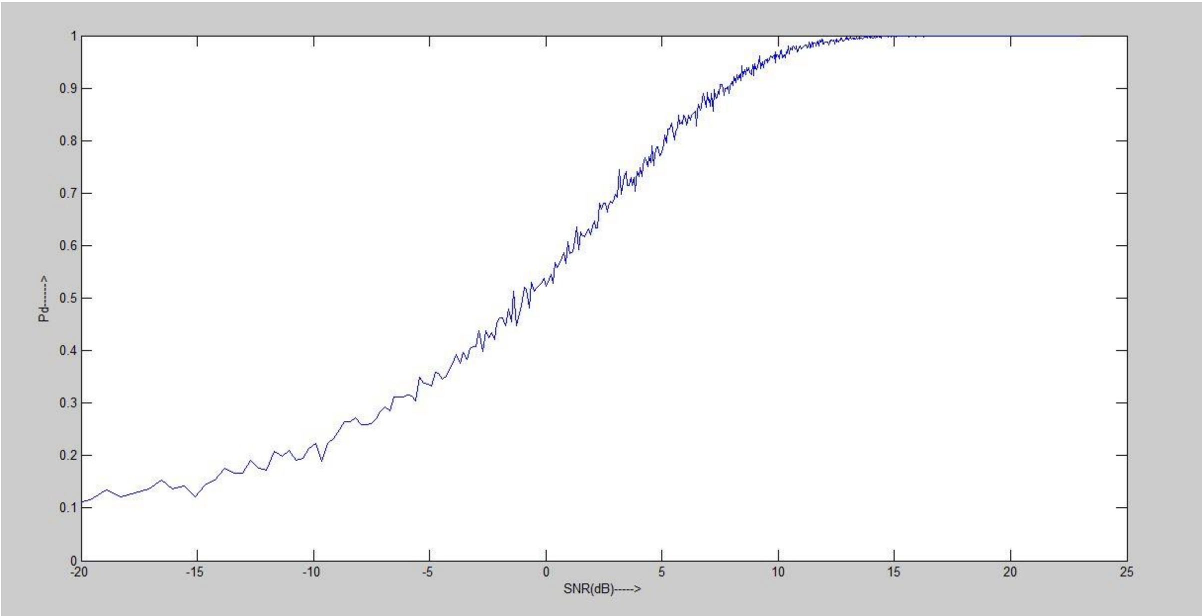


Figure 4.4: **Variation of Pd vs SNR**

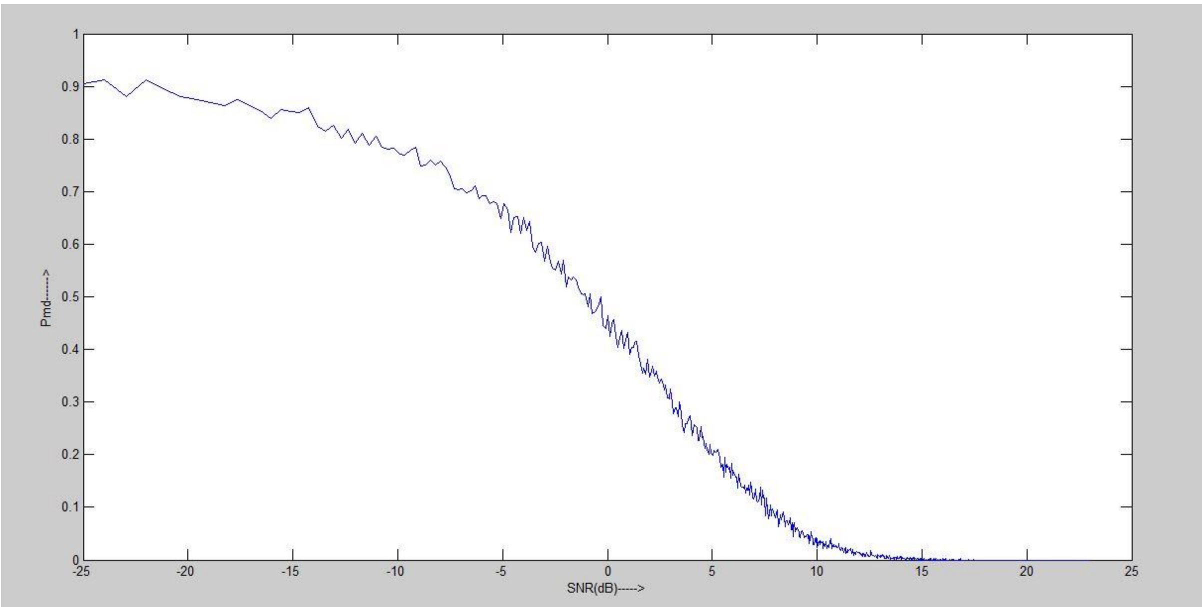
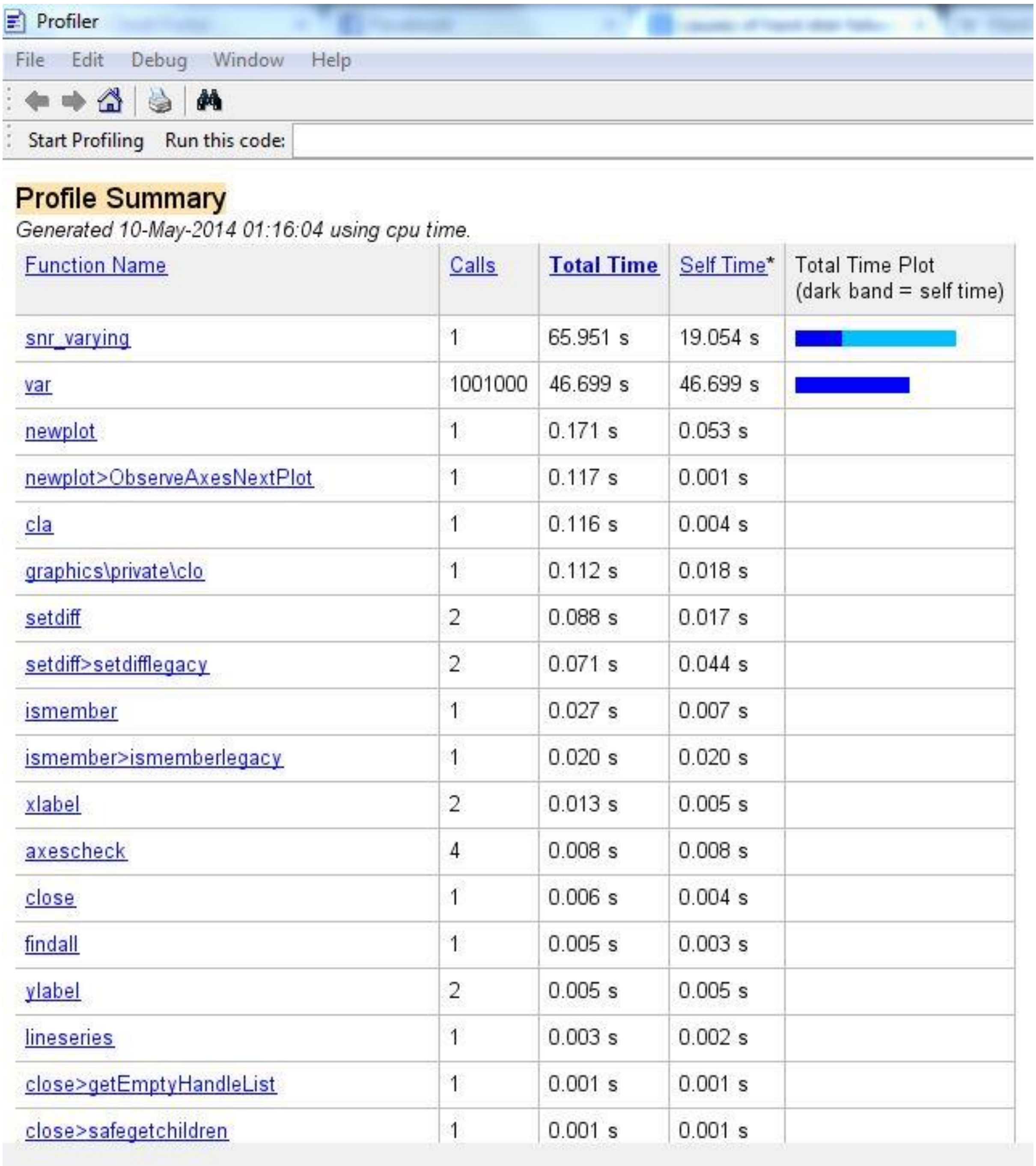


Figure 4.5: **Variation of Pmd vs SNR**



Profile Summary

Generated 10-May-2014 01:16:04 using cpu time.

Function Name	Calls	Total Time	Self Time*	Total Time Plot (dark band = self time)
snr_varying	1	65.951 s	19.054 s	
var	1001000	46.699 s	46.699 s	
newplot	1	0.171 s	0.053 s	
newplot>ObserveAxesNextPlot	1	0.117 s	0.001 s	
cla	1	0.116 s	0.004 s	
graphics\private\clo	1	0.112 s	0.018 s	
setdiff	2	0.088 s	0.017 s	
setdiff>setdifflegacy	2	0.071 s	0.044 s	
ismember	1	0.027 s	0.007 s	
ismember>ismemberlegacy	1	0.020 s	0.020 s	
xlabel	2	0.013 s	0.005 s	
axescheck	4	0.008 s	0.008 s	
close	1	0.006 s	0.004 s	
findall	1	0.005 s	0.003 s	
ylabel	2	0.005 s	0.005 s	
lineseries	1	0.003 s	0.002 s	
close>getEmptyHandleList	1	0.001 s	0.001 s	
close>safegetchildren	1	0.001 s	0.001 s	

Figure 4.6: **profile summary of Pd and Pmd vs SNR curve**

- As seen from the profile summary, it takes about 1 minutes for the simulation
- Low simulation time is a result of low computational complexity of energy detector

- # Results for Cyclo-stationary detector

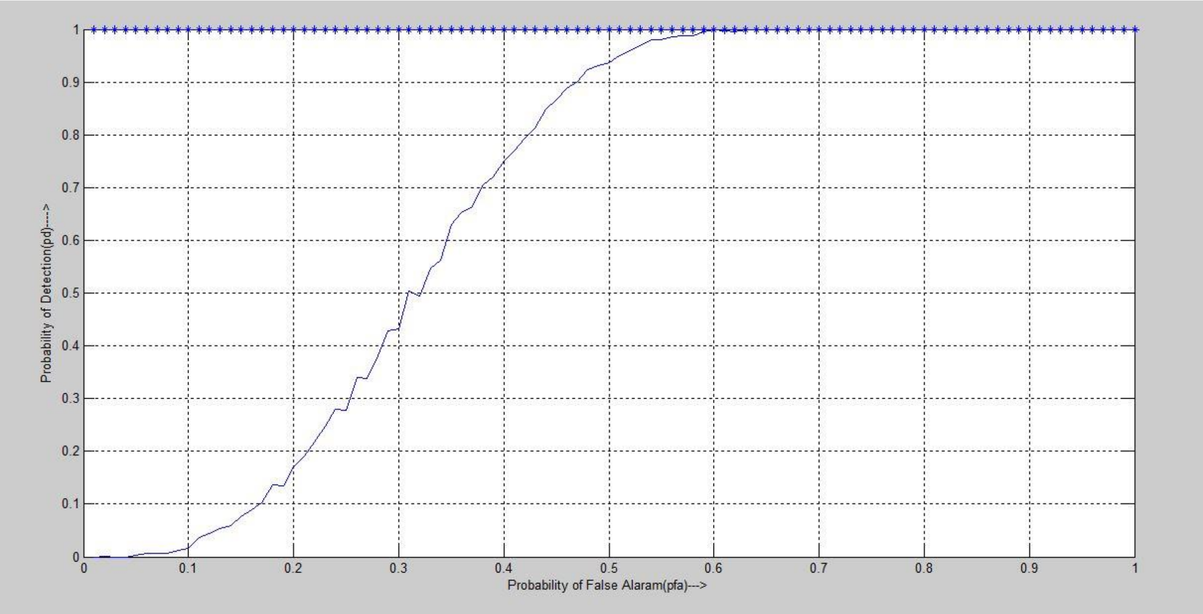
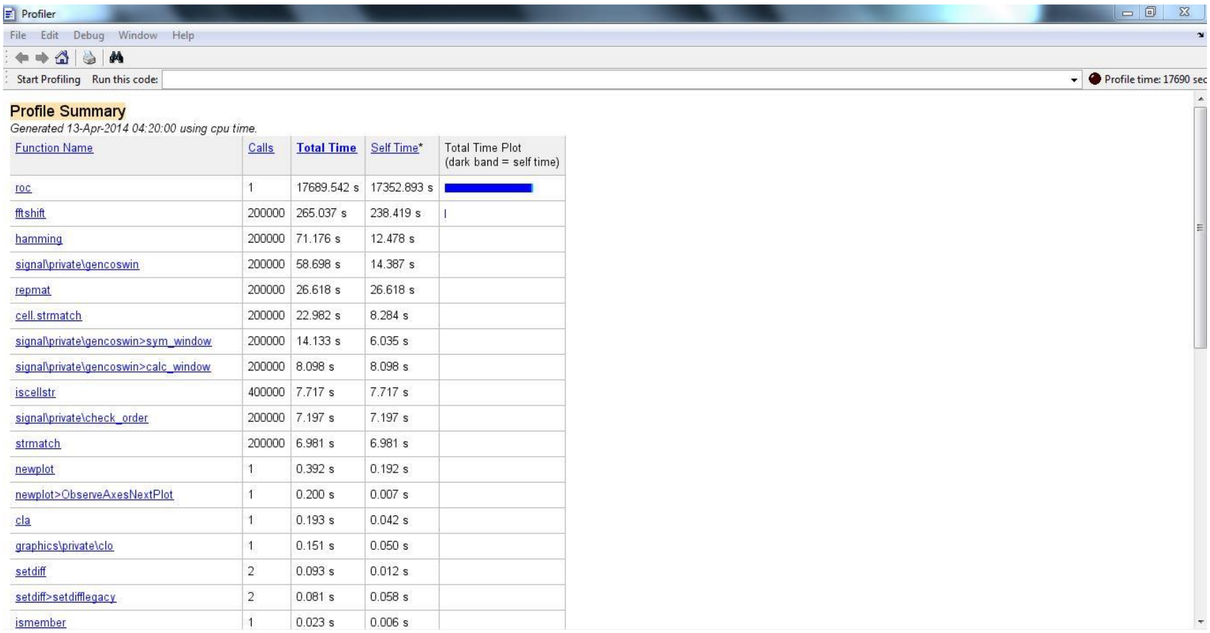


Figure 4.7: **ROC curve (Pd v's Pfa) for Cyclo-stationary detector**



Profile Summary

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Function Name	Calls	Total Time	Self Time*	Total Time Plot (dark band = self time)
roc	1	17689.542 s	17352.893 s	
fftshift	200000	265.037 s	238.419 s	
hamming	200000	71.176 s	12.478 s	
signal\private\gencoswin	200000	58.698 s	14.387 s	
repmat	200000	26.618 s	26.618 s	
cell.strmatch	200000	22.982 s	8.284 s	
signal\private\gencoswin>sym_window	200000	14.133 s	6.035 s	
signal\private\gencoswin>calc_window	200000	8.098 s	8.098 s	
iscellstr	400000	7.717 s	7.717 s	
signal\private\check_order	200000	7.197 s	7.197 s	
strmatch	200000	6.981 s	6.981 s	
newplot	1	0.392 s	0.192 s	
newplot>ObserveAxesNextPlot	1	0.200 s	0.007 s	
cla	1	0.193 s	0.042 s	
graphics\private\clo	1	0.151 s	0.050 s	
setdiff	2	0.093 s	0.012 s	
setdiff>setdifflegacy	2	0.081 s	0.058 s	
ismember	1	0.023 s	0.006 s	

Figure 4.8: **Profile summary of the ROC curve**

- The following curves show how **Cyclo-stationary detector** performs in noisy channel/environments. As seen from graph they perform well even in low SNR values starting from -7dB.

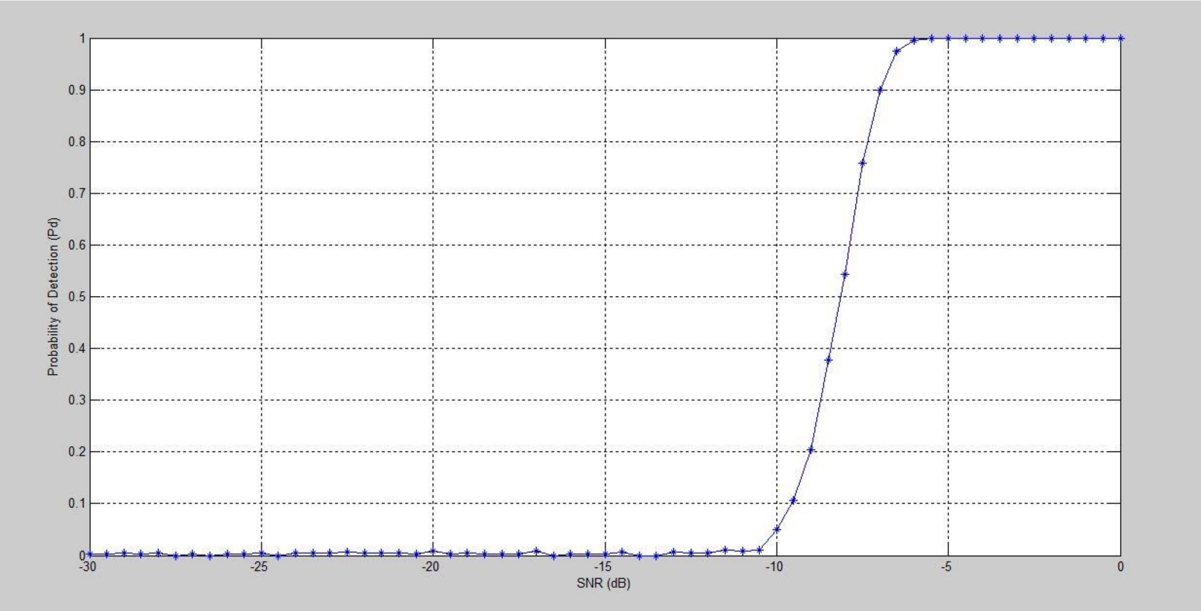
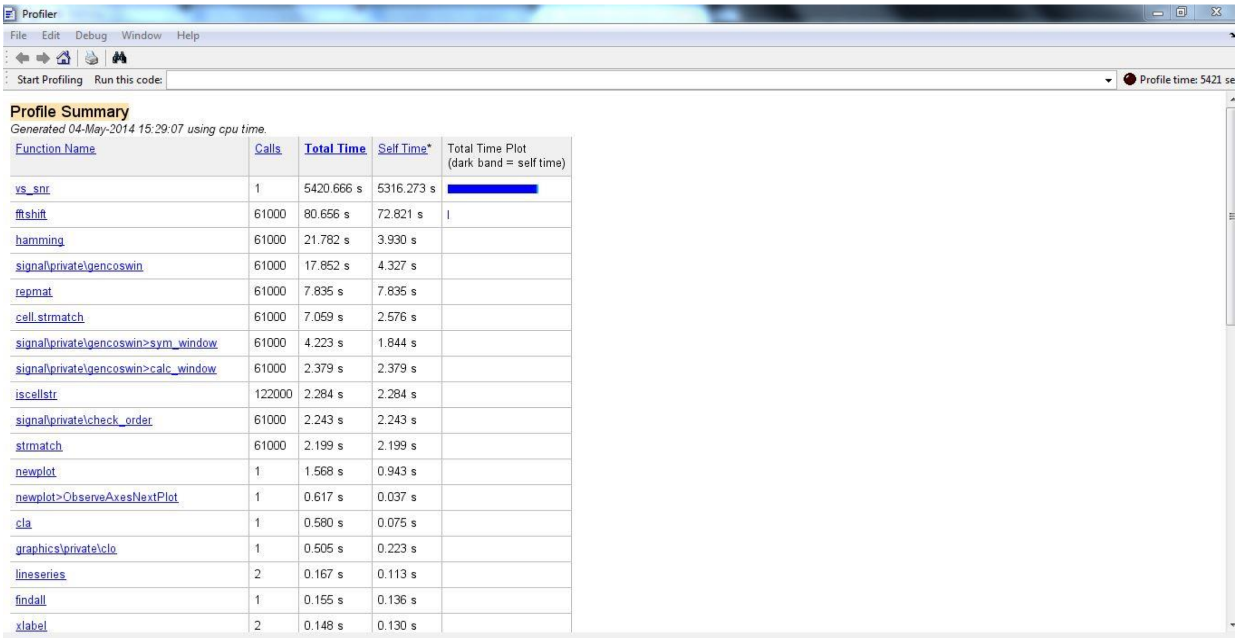


Figure 4.9: Variation of Pd vs SNR



Profiler
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Profile Summary

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Function Name	Calls	Total Time	Self Time*	Total Time Plot (dark band = self time)
vs_snr	1	5420.666 s	5316.273 s	
fftshift	61000	80.656 s	72.821 s	
hamming	61000	21.782 s	3.930 s	
signal\private\gencoswin	61000	17.852 s	4.327 s	
repmat	61000	7.835 s	7.835 s	
cell.strmatch	61000	7.059 s	2.576 s	
signal\private\gencoswin>sym_window	61000	4.223 s	1.844 s	
signal\private\gencoswin>calc_window	61000	2.379 s	2.379 s	
iscellstr	122000	2.284 s	2.284 s	
signal\private\check_order	61000	2.243 s	2.243 s	
strmatch	61000	2.199 s	2.199 s	
newplot	1	1.568 s	0.943 s	
newplot>ObserveAxesNextPlot	1	0.617 s	0.037 s	
cla	1	0.580 s	0.075 s	
graphics\private\clo	1	0.505 s	0.223 s	
lineseries	2	0.167 s	0.113 s	
findall	1	0.155 s	0.136 s	
xlabel	2	0.148 s	0.130 s	

Figure 4.10: Profile summary of Pd vs SNR curve

- As seen from the profile summary, it takes about some hours for the simulation to complete
- High simulation time is a result of extremely high computational complexity

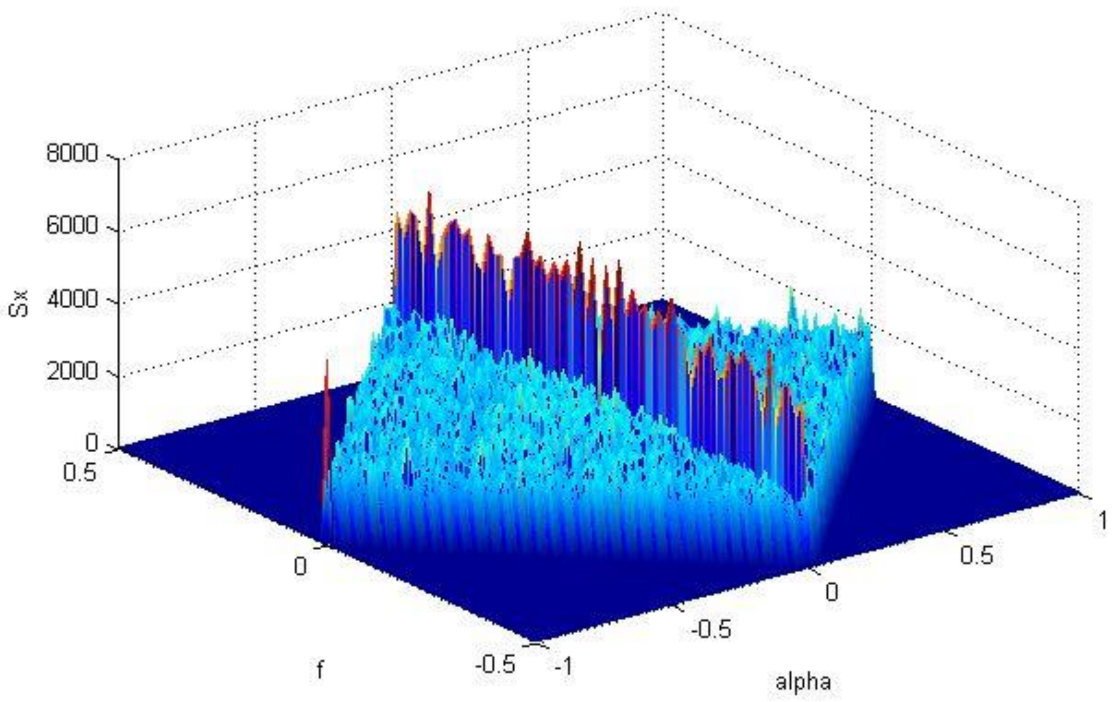

Figure 4.11: Cyclic spectrum of Additive White Gaussian Noise

- **S**ince AWGN has no cyclic components it is not Cyclo-stationary. Hence it has zero spectral components everywhere except when α=0.
- So only at zero cyclic frequency we observe the peaks in CSD curve for noise.
- Since AWGN does not contribute to any other peaks in CSD curve, hence the peaks in CSD curve will only be due to the signals. Hence the effect of noise is nullified.
- This leads to better performance of Cyclo-stationary detector in low SNR conditions

Computation cost of cyclo-stationary detector

- An established method of evaluating the algorithm complexity is to determine the number of floating point operations that must be performed [6].
- Assuming all data to be complex following is the computational requirements:-

1. Each N-point FFT requires (N/2) *$\log_2 N$ complex floating point multiplies or 2*N* $\log_2 N$ real floating point multiplies
2. Windowing requires 2*P*N' multiplications
3. Applying first Fourier transform requires 2*P*N'* $\log_2 N'$ multiplications
4. Down conversion requires 4*P*N' multiplications
5. Multiplication requires 4*N*N' multiplications
6. Applying Second Fourier transform requires 2*N*N'* $\log_2 N$ multiplications
7. In total we require 2*N'* (6*P + 4*N + (2*P + 2*N) * $\log_2 N$) multiplications

A typical example:-

If N=512

N’=32

L=4 and P=128

It gives the total number of required floating point operations=917504

- It shows that the computational complexity of the cyclostationary detector is very high

Chapter 5. Conclusion

Cognitive radio was introduced to utilize the unused spectrum efficiently to improve the spectrum utilization and hence to reduce spectrum scarcity. Spectrum sensing is one of the important aspects of cognitive radio network and in this thesis energy detector and cyclo-stationary detector are discussed thoroughly.

Energy detection method of spectrum sensing has its advantages as it is simple and easy to implement. Since no previous information about the signal is required for detection in this method of spectrum sensing, it is also known as semi blind spectrum sensing. Though easy to implement the performance of the energy detector deteriorates in noisy environments. In our simulations it is found that it performs well only at high SNR values. This led to the Cyclo-stationary method of spectrum sensing.

The Cyclo - stationary detector uses the periodicity in the primary signals which it receives to determine the presence of licensed users. It is very complex to implement and has very high computational complexity. Although its complexity is very high its performance in corrupted channels are praise worthy. The results of our project shows that it performs very well, even in the low SNR conditions starting from as low as -10dB and gives optimal results starting from -5dB.

5.1. FUTURE WORK

Based on the observations and results of our project, we propose to combine both methods to obtain the best performance at low cost. For any task, there is a fast method and a fine tune method with better precision and higher complexity. In case of spectrum sensing we can assume the energy detection as the fast method and the cyclo-stationary detection as the fine tune method. Given the SNR of the environment is known we can decide which algorithm to call for checking of presence of primary users. If the signal to noise ratio is high we can use energy detection and if the environment has low SNR we can use Cyclo-stationary detection.

This will help in increasing the efficiency of spectrum utilization without wasting unnecessary time and also reduce the cost. It is because Cyclo-stationary detection will only be used when the SNR is low, not always.

Also in our thesis, we have discussed the software implementation of the spectrum detectors. We can extend it to implement these detectors in hardware and use in real time systems. The security issue is another area in cognitive radio, which needs attention. Security can be enhanced by detecting the malicious user in the Cognitive radio network and minimize their effect.

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